The TVA Dollar-a-Day Energy Cost 235 m^2 Research Home

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ABSTRACT

In 2008, a demographic study was conducted on what represents the market for builder spec homes in the mixed-humid climate region served by a large electric utility. Several builders were interviewed and one was selected to construct a trilogy of research houses of similar size, orientation, window area, and exposure. One house captured what was representative builder "spec" construction in 2008, one was the same as the builder house but provided an extensive energy-efficiency retrofit package, and the third was a Home Energy Rating System (HERS) 34 high-performance house with highly efficient envelope, energy recovery ventilator, solar photovoltaics, and solar water heating.

This paper provides a measured performance comparison between the builder house with a HERS 101 and the HERS 34 high performance house. The envelope's measured comparisons cover the R-22 h·ft^2·°F/Btu (3.9 m^2·°C/W) hot box measured flash and blown-in fiberglass optimum value framed walls, R-49 h·ft^2·°F/Btu (8.6 m^2·°C/W) vented attic with radiant barrier on the underside of the roof sheathing, R-6 h·ft^2·°F/Btu (1.1 m^2·°C/W) triple layer windows, airtight construction, ach @ 50 Pa of 2.4, and zero energy duct loss to the outside. The HERS 34 high-performance house has a 2 ton seasonal energy efficiency ratio of 16 Btu/Wh (16.8 kJ/Wh), a heating season performance factor of 9.5 Btu/Wh (10 kJ/Wh) air-source heat pump compared to the International Energy Conservation Code *(ICC 2006) 2006 code-compliant air-source heat pumps with a total capacity of 4 tons (14 kW) in the builder house.*

These are research houses with identical simulated occupancies with the first full year of measured performance and a neutral cash flow analysis completed. These houses will be reconfigured every year with technology retrofits that will continue to strive toward neutral cash flow net-zero grid energy performance until at least 2012.

INTRODUCTION

This research project was initiated by Tennessee Valley Authority in March 2008 to inform the future direction of their residential retrofit and new house incentive program. The focal point encompasses three houses that are of similar size and design and are located within the same community with identical simulated occupancies. The first house is the "builder house." The second house is the "retrofit house," which used modifications that could be made to existing houses to improve their performance. The third house, Campbell Creek house 3 (CC3), is striving to maximize cost-effective energy efficiency. CC3 was designed by starting with the builder house plan and transforming it toward maximum cost-effective energy efficiency by 2012. The experimental plan calls for this to occur from 2009 through 2012.

The focus of this report is the 2512 ft^2 (233 m^2) two-story CC3. The builder house is representative of the other 35-plus units in this development. CC3 has ENERGY STAR® appliances and more advanced improvements in envelope and equipment as well as the addition of solar photovoltaic (PV) and solar water systems. The services provided in all three houses are identical to and consistent with the DOE Building America (BA) benchmark protocol (Hendron and Engebrent

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2006). The house controls lights, plug loads, refrigerator, dishwasher, clothes washer and dryer, oven, and showers.

Without the addition of the solar PV system, this house is predicted to achieve a whole-house savings of 55% compared to the builder house. By adding the solar PV system, a 68% energy savings is predicted. The floor plans, cross sections, and elevations of CC3 are provided by Dockery and Christian (2010). The location and orientation within the development of the builder house and CC3 are shown in Figure 1.

Both lots are south orientated, obtaining the greatest opportunity for south-facing roof area and year-round daylight as well as passive winter heat and shading of unwanted solar heat gain in the summer. The back of CC3 faces 26 degrees west of true south.

Of the conventional development that hosts these research houses, the developer requested that roof solar equipment visibility from the street be held to a minimum. As shown in Figure 2, the front of the builder house conveys no visible solar features.

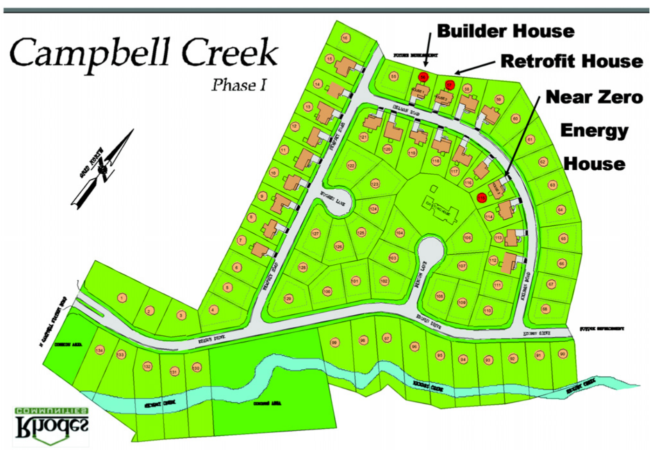

Figure 1 *Plot plan of house locations in East Tennessee.*

THE 68% ENERGY SAVINGS HOUSE

The single-family all-electric house shown in Figure 2 makes a strong step toward net zero energy (a net-zero-energy home is one that produces as much energy on site as it consumes on an annual basis). CC3 uses 68% less energy than the Builder Standard model. CC3 was instrumented with performance sensors to measure and record energy usage, temperature, and relative humidity of the interior and ambient environments; hot and cold water usage; heat pump functions; and other pertinent data. Fifteen-minute and in some cases one-minute data have been collected continuously since February 27, 2009. The models predict and the measurements support that this house, with typical American household occupancy in accordance with the BA benchmark and a 2.5 kW peak solar PV system, would cost an average of $1/day. The actual average residential rate of $0.093/kWh is used to calculate energy costs in 2009. The buyback for the solar generated by the PV system at the time was $0.213/kWh.

The total cost to construct CC3 was $353,570. Included in the cost are a solar water heater and a 2.5 kW peak solar electric system. All labor, taxes, profits, and overhead costs are included. Dockery and Christian (2010) provides a detailed cost breakdown for CC3.

CC3 Uncovered

CC3's south elevation is shown during construction in Figure 3.

The wall construction is optimum value framing consisting of 2 × 6s on 24 in. center (51 × 152 cm @ 0.6 m), 1/2 in. (13 cm) structural insulated sheathing, and 1 in. (25 cm) of closed cell spray foam; the remainder of the interior cavity, shown in Figures 4–6, is filled with blown-in fiberglass.

Figure 5 shows the single laminated veneer lumber structural header, allowing longer window and door opening spans than standard dimensional lumber, as well as more cavity insulation.

Figure 2 *Dollar-a-day CC3 builder spec house.*

Figure 3 *South elevation of CC3.*

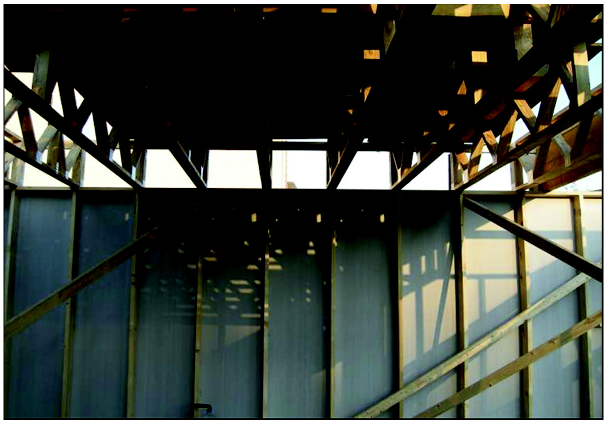

Figure 4 *First floor framing aligned with the second floor trusses—note the single top plate.*

Figure 5 *Advanced header framing of CC3.*

Figure 6 *Insulation under the cantilevered floor.*

The cantilevered floor over the front porch, open headers, and wall cavities were sprayed on all interior surfaces with at least 1 in. of foam, and the remainder of the cavity spaces were filled completely with blown-in fiberglass.

Figure 7 illustrates the triple-pane windows used in the fenestration of CC3. These windows have a U-factor of 0.15 Btu/h·ft^2·°F (0.86 W/h·m^2·°C) and a solar heat gain coefficient of 0.26.

Figure 7 *Triple-pane windows.*

TECHNOLOGIES

The building envelope and mechanical devices used in CC3, compared to those used in the builder house, are provided in Tables 1 and 2. CC3 has a validated Home Energy Rating System (HERS) index of 34. Without the PV system, CC3 achieved a HERS index of 47, and without the solar water heater it increased to 53. CC3 is equipped with a ~60 ft^2 (5.6 m^2) roof-mounted drainback solar water heater and PV system rated at 2.5 kWp.

Foundation

Figure 8 illustrates the foundation detail used for CC3. A continuous 2 in. (51 cm) layer of extruded polystyrene was placed on the inside of the foundation masonry wall from the top of the footing to the bottom of the slab. A continuous layer of 2 in. (51 cm) extruded polystyrene was placed in continuation of the 1 in. (25 cm) separating the slab from the header block and along the slab edge. The final grade was sloped 5% (at least 6 in. [0.15 m] for 10 ft [3 m]) away from both foundations.

Walls—Optimum Value Framing

Houses constructed of 2 × 6 framing at 24 in. (0.6 m) centers allow for added insulation. Typically with 2 × 4 construction a whole-wall value of R-11 h·ft^2·°F/Btu (1.9 m^2·°C/W) is attained, but with 2 × 6 construction a value of R-22 h·ft^2·°F/Btu (3.9 m^2·°C/W) is achieved in this design. Two-stud corners not only allow for more insulation, but they

Table 1. Envelope Technology Package in Builder House and CC3

	Builder House	CC3
Stories	2	2
Floor	2512 ft^2 (233 m^2)	2512 ft^2 (233 m^2)
Conditioned volume	23,192 ft^2 (657 m^2)	23,192 ft^2 (657 m^2)
Foundation	Slab insulated with 1 in. (25 cm) XPS at edge	Slab insulated with 2 in. (51 cm) XPS, 24 in. (0.61 m) vertical
Walls	2 × 4 standard framing, double top plates, uninsulated headers, 3-stud corners, OSB exterior sheathing, R-13 h·ft^2·°F/Btu (2.3 m^2·°C/W) batts, framing factor of 0.23	2 × 6 OVE @ 24 in. wood frame, single top plates, single LVL insulated headers, 2-stud corners, DOWsis R-2.74 h·ft^2·°F/Btu (0.5 m^2·°C/W) sheathing, 1 in. of spray foam insulation and Spider R-22 h·ft^2·°F/Btu (3.9 m^2·°C/W) (hot box test measured)
Attic	Blown-in fiberglass R-30 h·ft^2·°F/Btu (5.3 m^2·°C/W) insulation	Blown-in fiberglass R-49 h·ft^2·°F/Btu (8.6 m^2·°C/W) insulation
Windows	Single-pane U = 0.5 Btu/h·ft^2·°F (2.8 W/h·m^2·°C), SHGC = 0.56	Triple-pane U = 0.15 Btu/h·ft^2·°F (0.85 W/h·m^2·°C), SHGC = 0.26
Doors	1 insulated door U-factor = 0.4 Btu/h·ft^2·°F (2.3 W/h·m^2·°C)	2 insulated doors with insulated U-factor = 0.29 Btu/h·ft^2·°F (1.6 W/h·m^2·°C)
Roof	Truss system, 3/4 in. (19 cm) OSB	Truss system, 3/4 in. (19 cm) OSB with LP Techshield radiant barrier
Roofing	0.75 solar absorptance, composition shingles, attic ventilation ratio 1 to 300	0.85 solar absorptance, compositions shingles, attic ventilation ratio 1 to 300
Infiltration	ach (50 Pa) = 5.7	ach (50 Pa) = 2.40

ach = air changes per hour; LVL = laminated veneer lumber; OSB = oriented strand board; OVE = optimum value engineering; SHGC = solar heat gain coefficient; XPS = extruded polystyrene

Table 2. Equipment Technology Packages in Test Houses

House	Builder House	CC3 2-Story
Heating and cooling	SEER = 13 Btu/Wh (13.7 kJ/Wh), SHR = 0.75, cooling capacity = 48 kBtu/h (57 kJ/h), heating capacity = 48 kBtu/h (51 kJ/h), 1620 cfm (46 cmm), HSPF = 7.7 Btu/Wh (8.1 kJ/Wh)	SEER = 16 Btu/Wh (16.9 kJ/Wh), single 2 ton air-source HP, dual-speed compressor, variable-speed ECM, indoor fan cooling capacity = 24.7 kBtu/h (26 kJ/h), HSPF = 9.5 Btu/Wh (10 kJ/Wh)
Thermostat settings	76°F (24°C) in summer, 71°F (22°C) in winter	76°F (24°C) in summer, 71°F (22°C) in winter
Mechanical ventilation	30 cfm (0.85 cmm) continuous exhaust from bath fan	ERV exhausting three baths and the kitchen and supplying the three bedrooms and the great room
Duct location	Outside conditioned space, R-5 h·ft^2·°F/Btu (0.9 m^2·°C/W), supply area = 460 ft^2 (43 m^2), return area = 85 ft^2 (8 m^2), duct air leakage = 11.8%, 183 cfm (5.2 cmm) to the outside	Except for bonus supply runout (~6 ft [1.8 m]), the supply and return ducts are inside conditioned space, R-6 h·ft^2·°F/Btu (1.1 m^2·°C/W), and 0 air leakage to the outside
Air handler location	One in attic, one in garage	Inside conditioned space
Water heater	Electric 50 gal (189 L) capacity, EF = 0.91, usage = 66 gal/day (250 L/day), set temperature = 125°F (52°C)	Solar water heater, 85 gal (319 L), EF = 0.91, set temperature = 125°F (52°C), 52 ft^2 (4.8 m^2) collector area, electric pumps, usage = 52 gal/day (195 L/day) (lower because of the ENERGY STAR washer in CC3)
Lighting	100% incandescent	100% fluorescent
Solar PV system	None	12 208 W polycrystalline 2.5 kWp

ECM = electronically commuted motor; EF = energy factor; ERV = energy recovery ventilator; HP = heat pump; HSPF = Heating Seasonal Performance Factor; PV = photovoltaic; SEER = seasonal energy efficiency rating

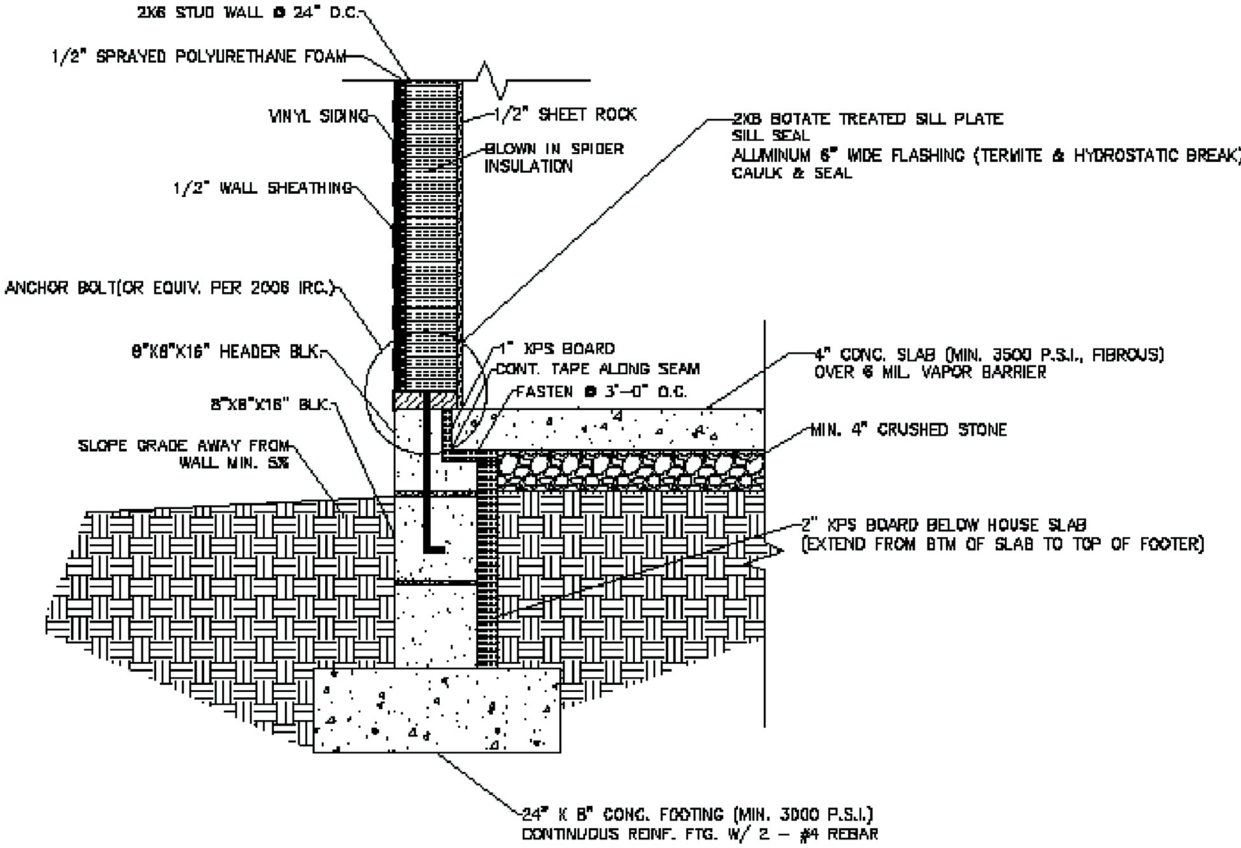

Figure 8 *Foundation detail of CC3.*

also reduce the amount of thermal shorts of three-stud corners. The insulation added to the wall cavities was an inch of closed cell spray foam, and then the remainder of the cavities were filled with blown-in fiberglass. The sheathing used on the exterior walls is 1/2 in. structural insulated sheathing with an R-value of 2.74 $h \cdot ft^2 \cdot °F/Btu$ (0.5 $m^2 \cdot °C/W$) measured using ASTM 518 (ASTM 2002). All seams were taped providing manufactured certified structural lateral bracing and transverse loads and a water-resistive and air barrier.

Windows

The National Fenestration Rating Council recommends that, for all-electric, mixed-humid-climate houses with energy costs around $0.093/kWh, the U-factor be at least 0.34 and the solar heat gain coefficient should be no higher than 0.33. The visible transmittance for the windows used on CC3 was 0.47. The windows specifically designed for the test houses were vinyl foam insulated frames, single-hung, triple-layer windows. The sixteen-window package for CC3 has an estimated installed cost of $10,000. A more recent cost of these windows was obtained in September 2009 at $8.30/$ft^2$ ($0.89/$m^2$) above the cost of the builder house windows. This is a $2465 cost difference. The windows are installed after the sheathing is fully taped. For details on how the windows were installed, see Dockery and Christian (2010). The window installer on this project insisted that the windows be sealed at the bottom outside flange. This is not recommended practice, since you want to enable any water leaks into the window itself or the rough opening to drain to the outside. Each window and door was panned and weather lapped flashings were installed.

Roof and Ceiling

The roof of CC3 is constructed with a truss system consisting of 3/4 in. (19 cm) oriented strand board and an underside laminate radiant barrier. Next, #30 asphalt-impregnated roofing paper was weather-lapped as soon as the sheathing was installed. The roofing system is three-tab composite shingles. The dead load calculations used to specify the truss system included the weight of the solar collectors for the PV system and the collectors for the solar hot water heater. In order to be solar ready, it may be advantageous to assume total south-facing roof area coverage with solar PV modules for dead load design calculations.

Heat Pump

A SEER 16, Btu/Wh (16.8 kJ/Wh), HSPF 9.5 Btu/Wh (10 kJ/Wh) split air-source heat pump was installed for the first year of testing. About 35% of the heat pump energy consumption was due to resistance backup heat from December 2009 through February 2010. A variable refrigerant flow system would reduce the amount of backup resistance heat during the coldest months and will replace the current unit in September 2010. A direct-current commutating fan HVAC indoor fan motor could be used to meet the ASHRAE Standard 62.2 (ASHRAE 2004) ventilation air requirements using the low speed of the heat pump. This would be about a $500 solution. In this house, a completely separate energy recovery ventilator (ERV) with its own duct system is used for bringing in fresh air and recovering about 50% of the heat contained in the exhaust conditioned air. This is a $3500 solution.

The eighth edition of *Manual J* (Rutkowski 2004) was used to calculate the heating and cooling design loads for the whole (2512 ft^2 [233 m^2]) house. Only one HVAC unit with a two-zoned distribution system was sized for the entire house. One thermostat-controlled motorized trunk served upstairs and a second served downstairs.

CC3 is equipped with a 2 ton (12.7 MJ) air-source heat pump. The heat pump system has a dual-speed compressor and a variable-speed electronically commuted motor with an indoor fan. The design heating load was 23,612 Btu/h (24.9 MJ/h), and the design sensible cooling load was 15,729 Btu/h (16.6 MJ/h). The estimated coefficient of performance at peak was assumed to be 2.0 and the SEER, 16 Btu/Wh (16.9 kJ/Wh). In the builder house, which has 112 ft^2 (10 m^2) less floor area, a 2.5 ton (31.6 MJ/h) heat pump is located in the unconditioned attic, serving upstairs, and a second 1.5 ton (22 MJ/h) unit is installed in the garage, serving downstairs.

Ducts

The blower equipment was located to allow for the shortest duct runs allowed by the fixed floor plan. All CC3 ducts are located in the conditioned space except for a 6 ft (1.8 m) run going to the bonus room. This duct was well insulated and air sealed and resulted in zero duct blaster measured air leakage to the outside. The duct system in this house serves two zones. In the bonus room and each bedroom, 8 in. (0.2 m) jump ducts have been placed in the attic connecting the often closed-off bedroom space to the hallway single central return. Above the returns on the main and second levels, programmable thermostats were positioned. To complete this zone-controlled system, a 6 in. (0.15 m) dump duct is run to the middle height of the two-story foyer. This duct always remains open to allow additional supply air when only one of the zones calls for conditioned air.

Manual D (ACCA 2006) was used in sizing the ducts for CC3. The needed cubic feet per minute for each room comes from the *Manual J* room-by-room load calculation (Rutkowski 2004). The main supply trunk is hard piped and sealed with mastic. Insulated ducts lessen condensation risk. Short flex duct runs are used to connect the main supply trunk with floor and ceiling supply registers in every room except the laundry and bathrooms.

A duct blaster test was conducted on CC3. This test is done in order to measure the total air leakage of the duct system, along with the amount of air leakage to the outside. The results from this test were 80 cfm (2.7 cmm) of total leakage and zero leakage to the outside. Total duct leakage of 9% is considered very good, particularly when the ducts are inside the conditioned space.

Ventilation Air Treatment

CC3 has an ERV that has six exhaust ducts and five supply ducts. The ventilator is set to provide an automatic average of 30 cfm (0.85 cmm). Manual override controls are located in each bathroom and the kitchen for when additional ventilation is needed. The design was to meet the requirements of the 2007 edition of ASHRAE Standard 62.2 (ASHRAE 2007) and, in the case of the CC3, the total ventilation and infiltration should be capable of providing 63.7 cfm (1.8 cmm) for the three-bedroom residence. The HVAC system does an excellent job of maintaining the desired thermostat setting of 76°F (24°C) in the summer and 71°F (21°C) in the winter, in both the builder house and CC3.

Electrical Wiring

In wood-frame construction, like that of CC3, the electric outlets are frequently a major residual leakage path after dedicated envelope air tightening. In CC3, the high-density spray foam insulation air-sealed the areas around the electric outlets.

Lighting

CC3 is equipped with pin-based ENERGY STAR rated 100% florescent lighting. The plan was to add light-emitting diode (LED) lighting in September 2010. For lighting fixtures, globe bulbs were used in the upstairs bathroom. Under-cabinet mounted fluorescent lights are installed in the kitchen and work very well. The actual cost of the pin-based fixtures and the need for special orders from the builder's lighting supply chain resulted in incremental costs for lighting in this house of $2,506.38. This high cost actually made the efficient lighting package not meet positive neutral cash flow. The incremental cost of the identical retrofit house lights compared to builder house lights of $883.19 was assumed for the neutral cash flow analysis and still delivered the same lighting energy efficiency.

PV System

Homeowners are paid $0.12/kWh above the standard residential rate for all the alternating-current solar power generated in a grid-tied arrangement by Tennessee Valley Authority's Green Power Switch® Generation Partners℠ program (TVA 2010). Figure 9 shows the 12 208 W solar modules on the right side of the south-facing roof. There remains enough space on the south roof to double the solar PV capacity.

Figure 9 *Twelve 208 W modules mounted on the south-facing roof.*

The 12 modules add 721 lb (327 kg) of dead load to the roof and cover 796 ft^2 (74 m^2) of roof area. The added roof dead load attributable to the solar modules amounts to less than 1 lb/ft^2 (5 kg/m^2).

The January 2009 homeowner cost for 12 208 W modules was $10,400. The inverter, AC and DC cutoffs, and module roof mounting hardware was $3,001.24; the module installation was $2002.41; and the electrician cost to wire the system and install the whole house cutoff was $2405. The total equipment and installation cost was $17,808 before incentives.

Water Heating

Figure 9 shows the two solar water heater collectors installed on the left side of the back south-facing roof. Including the cost of the 85 gal (322 L) storage and drainback tanks, this system had a total installed cost of $10,333 in 2008. After the federal tax incentive, this cost drops to $6888.60. This two-panel system meets the Solar Rating and Certification Corporation standard (SRCC 2010). The two panels are angle-mounted at 40° to the roof. The roof slope is 23°. This system utilizes a heat exchanger pumping system external to the 85 gal (322 L) storage tank. This system controls the entire pumping operation of the solar water heating. The storage tank has an energy factor of 0.92

Appliances

The dishwasher, refrigerator, and clothes washer are all ENERGY STAR labeled. These appliances are automatically operated in accordance with the BA profile of three occupants (Hendron and Engebrent 2009). The refrigerator doors are robotically controlled to open and close in response to a daily schedule representative of typical users. The dishwasher, clothes washer, oven, and clothes dryer are also simulated through various cycles.

Table 3. Building America Site Energy Consumption

	Annual Site Energy (kWh)		
End Use	**Builder**	**CC3**	**% Savings**
Space heating	10697	2958	72%
Space cooling	2685	1225	54%
Domestic hot water	4215	1111	74%
Lighting	2320	695	70%
Refrigerator	501	421	16%
Washer	105	101	4%
Dryer	891	774	13%
Dishwasher	206	206	0%
Range	605	605	0%
Plug loads	3422	3422	0%
Total usage	25647	11518	55%
Site generation	0	3409	
Net energy use	25647	8109	68%

ENERGY COSTS

Costs per Day

The average electricity rate in 2009 for CC3 was $0.093/kWh, which is less than the national average of $0.1176/kWh (EIA 2010).

CC3 has an average electric cost of about a $1/day. Compared to CC3, the builder house has an average cost of $6.53/day. Shown in Table 3 are the solar generation and energy consumption of CC3 and the builder house.

Measured Data

The net measured average daily energy consumption for the months from June 2009 through January 2010 is displayed in Table 4. The second column shows data measured by the data acquisition system (DAS) and the third column shows data measured by the electric utility revenue meter; there is only a slight difference in the two. The "Solar Generated" column in Table 5 shows the simulated data from the calibrated model using measured data from the PV system of CC3 with a 6/12 roof slope. In parentheses is actual measured monthly solar PV alternating-current generation.

The monthly energy consumption data, which include solar PV, cooling and heating loads, and solar water heater values, in Table 4 are based on the simulations generated by the EnergyGauge (FSEC 2009) model. The values in parentheses are measured data from July 09 through Feb 2010. The simulated occupancy control in these research houses continued to improve from July 09 until March 10. The Typical Meteorological Year version 3 (TMY3) data for Knoxville, TN (RReDC 2008), is used to model the house, not the actual weather, during this period. In general, there is reasonable agreement in the major sub-metered data and the model predictions.

On June 6, 2009, a series of blower door tests was conducted on CC3 in order to determine the airtightness of the envelope. The blower door depressurized the house at 50 Pa in order to determine the natural air changes per hour (ach). This resulted in 2.5 ach. Also on June 6, 2009, a series of duct blaster tests was conducted in order to calculate the total cubic feet per minute (cfm) of air leakage to the outside. From this test we found a total leakage of 80 cfm (2.3 cmm) and 0 cfm (0.3 cmm) of air leakage to the outside. The result of 0 cfm of air leakage to the outside verifies the major benefit of placing the ducts within the conditioned space. The builder house had a measured 183 cfm (5.2 cmm) @ 25 Pa leakage to the outside.

ENERGY SAVINGS COMPARED TO THE BUILDER HOUSE

With the usage of the EnergyGauge software (FSEC 2009), a calibrated model was built of CC3 and the builder house. In comparison to the builder house, CC3 requires 68% less energy. Without the solar PV system, the two-story CC3 is a 55% energy-saving house compared to the builder house. EnergyGauge generates a HERS index of 34 for CC3, qualifying it for the builder federal tax credit of $2000. The builder house HERS index is 101. Table 6 shows the incremental energy savings starting with the builder house and working one feature at a time to CC3. When looking at the heating, cooling, lighting, and domestic hot water loads, there are energy savings of 54%–72%.

The order in which the technologies were added to the builder house is based on the ease of retrofitting at the estimated lowest cash flow, from changing a lightbulb to tearing into walls. With all of the features and equipment used, CC3 saves a total of $2040 per year. Included in the savings is the PV system, with a $0.12/solar kWh buyback above the local residential rate.

Table 4. Whole-House Energy Comparison between DAS and Utility Revenue Meter for June 2009

Month	DAS Measured Net Energy, kWh/day	Utility Revenue Meter, kWh/day	Difference DAS vs. Utility, %
June	43.5	44.7	2.7
July	27.3	N/A, meter switched	
August	23.0	23.3	1.3
September	20.8	20.9	0.5
October	16.9	17.1	1.1
November	13.3	14.1	5.7
December	33.1	35.1	5.7
January	48	46.5	–3.2

Table 5. CC3 Energy Use with Typical Building America Occupancy (July 2009–February 2010)

Month	Space Heat, kWh	Space Cool, kWh	Solar Water Heating, from EnergyGauge	Other, from EnergyGauge	Total Electric, kWh	Solar Generated, kWh
Jan-10	823 (1089)	0	169	529	1521 (1681)	–205 (–194)
Feb-10	659 (785)	0	138 (136)	477	1274 (1505)	–227 (–167)
Mar-10	329 (358)	0	109	529	967 (958)	–294 (–242)
Apr-10	176	23	69	512	780	–340 (–320)
May-10	0	98	73	529	700	–337 (–317)
Jun-10	0	247	51	512	810	–346 (–375)
Jul-09	0	345 (332)	51 (67)	529	925 (1192)	–349 (–345)
Aug-09	0	333 (354)	48 (24)	529	910 (1073)	–345 (–360)
Sep-09	0	159 (216)	57 (105)	512	728 (876)	–297 (–253)
Oct-09	112	20 (45)	75 (85)	529	736 (746)	–264 (–221)
Nov-09	253 (159)	0	112 (73)	512	877 (649)	–219 (–251)
Dec-09	605 (635)	0	157 (160)	529	1291 (1182)	–186 (–156)
Total	2958	1225	1111	6224	11519	–3409
Annual $	$275	$114	$103.3	$343	$1071	–$726
Daily cost			$0.28	$0.94	$2.93	–$1.99

Note: Values in parentheses are measured values.

Table 6. CC3 Individual Technology Energy Savings compared to the Builder House

Increment	Site Energy, kWh	Estimated Source Energy, MBtu	National Energy Savings, %	Average Cost, $/yr	Builder Standard (Local Costs)			
					Energy, $/yr	Cost Savings, %	Measured Value, $/yr	Package Savings, $/yr
BA benchmark	33070	376.5		$3,889	$3,076			
Builder Standard (BSP)	25647	292.0	0%	$3,016	$2,385	0%		
BSP + CFL	24242	276.0	5%	$2,851	$2,255	5%	$131	$131
BSP ++ ENERGY STAR fridge	24171	275.2	6%	$2,843	$2,248	6%	$7	$137
BSP ++ ENERGY STAR washer and dryer	23232	264.5	9%	$2,732	$2,161	9%	$87	$225
BSP ++ R-49 attic insulation	22635	257.7	12%	$2,662	$2,105	12%	$56	$280
BSP ++ U = 0.2 doors	22487	256.0	12%	$2,644	$2,091	12%	$14	$294
BSP ++ SEER 16 heat pump	20257	230.6	21%	$2,382	$1,884	21%	$207	$501
BSP ++ move two windows from west and east to south	20230	230.3	21%	$2,379	$1,881	21%	$3	$504
BSP ++ windows double-pane to triple-pane	18778	213.8	27%	$2,208	$1,746	27%	$135	$639
BSP ++ ducts inside conditioned space	15080	171.7	41%	$1,773	$1,402	41%	$344	$983
BSP ++ improved ach from 5.8 to 2.4 @ 50 Pa	14769	168.2	42%	$1,737	$1,374	42%	$29	$1,012
BSP ++ ERV	14552	165.7	43%	$1,711	$1,353	43%	$20	$1,032
BSP ++ solar water heater	12847	146.3	50%	$1,511	$1,195	50%	$159	$1,190
BSP ++ improved walls from 13 to 22	11959	136.2	53%	$1,406	$1,112	53%	$83	$1,273
BSP ++ slab edge insulation of R-10	11584	131.9	55%	$1,362	$1,077	55%	$35	$1,308
BSP ++ improved floors over garage	11570	131.7	55%	$1,361	$1,076	55%	$1	$1,309
BSP ++ radiant barrier under roof sheathing	11518	131.1	55%	$1,355	$1,071	55%	$5	$1,314
BSP ++ solar PV	8109	92.3	68%	$545	$345	86%	$726	$2,040

CFL = compact fluorescent lightbulb; ERV = energy recovery ventilator; PV = photovoltaic

CONSTRUCTION COST

A detailed cost breakdown of the actual cost to construct CC3 in 2008 is provided by Dockery and Christian (2010). The cost to construct CC3 is $353,570, or $141/ft^2 ($13.10/m^2). The incremental cost to construct the energy features of CC3 compared to the builder house is $30,684 after incentives.

NEUTRAL CASH FLOW ANALYSIS

Table 7 shows the neutral cash flow analysis using the BA researched definition (Hendron 2010). The amortized cost estimates assume a 30-year loan at 7% interest. This is about the same as a 13-year simple payback. The analysis is conducted comparing CC3 to the builder house. Using the actual local electric rate for the builder house, this comes out to a $2,385 total energy cost for the builder house. The actual measured energy cost for the builder house after one year was 21,000 kWh, or $1953; however, the simulated occupancy was not operational from April 1, 2009, through June 1, 2009. In addition, as of January 1, 2010, all three research houses, including the builder house, are ventilated an average of 30 cfm (0.85 cmm), which is the value used in the model simulation. The builder house has slab edge insulation, which is not included in the model because the builder did not install this in the other three dozen houses in the development. Another difference is that the builder house is only 2400 ft^2 (223 m^2), not 2512 ft^2 (233 m^2) as modeled. The larger size of CC3 resulted from exercising the builder option of adding a pantry, which also houses the mechanical equipment completely inside the conditioned space.

Table 7. Building America Cash Flow Analysis for CC3

Increment	Site Energy, kWh	Builder Standard (Local Costs), $/yr	Measured Value, $/yr	Package Savings, $/yr	Energy Savings from Technology, kWh	Incremental Cost, $	Amortized Cost, $	Annual Cost, $	Meet Neutral Cash Flow, $
BA benchmark	33070	$3,076							
Builder Standard (BSP)	25647	$2,385			7423				
BSP + CFL	24242	$2,255	$131	$131	1405	$883	$71	–$60	yes
BSP ++ ENERGY STAR fridge	24171	$2,248	$7	$137	71	$132	$11	$4	no
BSP ++ ENERGY STAR washer and dryer	23232	$2,161	$87	$225	939	$700	$56	–$31	yes
BSP ++ R-49 attic insulation	22635	$2,105	$56	$280	597	$300	$24	–$32	yes
BSP ++ U = 0.2 doors	22487	$2,091	$14	$294	148	$253	$20	$6	no
BSP ++ SEER 16 heat pump	20257	$1,884	$207	$501	2230	$1,000	$80	–$128	yes
BSP ++ move two windows from west and east to south	20230	$1,881	$3	$504	27	$2	$0	–$2	yes
BSP ++ windows double-pane to triple-pane	18778	$1,746	$135	$639	1452	$1,900	$152	$17	no
BSP ++ ducts inside conditioned space	15080	$1,402	$344	$983	3698	$2,000	$160	–$184	yes
BSP ++ improved ach from 5.8 to 2.4 @ 50 Pa	14769	$1,374	$29	$1,012	311	$800	$64	$35	no
BSP ++ ERV	14552	$1,353	$20	$1,032	217	$3,000	$240	$219	no
BSP ++ solar water heater	12847	$1,195	$159	$1,190	1705	$9733	$777	$618	no
BSP ++ improved walls from 13 to 22	11959	$1,112	$83	$1,273	888	$4,508	$360	$277	no
BSP ++ slab edge insulation of R-10	11584	$1,077	$35	$1,308	375	$400	$32	–$3	yes
BSP ++ improved floors over garage	11570	$1,076	$1	$1,309	14	$500	$40	$39	no
BSP ++ radiant barrier under roof sheathing	11518	$1,071	$5	$1,314	52	$207	$17	$12	no
Total energy-efficient investment	11518	$1,071	$1,314	$1,314	14129	$26,318	$2,101	$787	no
Total energy-efficient investment with incentives	11518	$1,071	$1,314	$1,314	14129	$19,219	$1,534	$220	no
Site generation (solar PV)	3409	$726	$726			$17,809	$1,422		
Total with site generation	8109	$345		$2,040	17,538	$44,127	$3,523	$1,483	no

CFL = compact fluorescent lightbulb; ERV = energy recovery ventilator; PV = photovoltaic; TVA = Tennessee Valley Authority

Table 7. Building America Cash Flow Analysis for CC3 *(continued)*

Increment	Site Energy, kWh	Builder Standard (Local Costs), $/yr	Measured Value, $/yr	Package Savings, $/yr	Energy Savings from Technology, kWh	Incremental Cost, $	Amortized Cost, $	Annual Cost, $	Meet Neutral Cash Flow, $
Rebates/Incentives									
Energy-efficient builder house ($2000)						$2,000	$160		
Solar water heater tax incentive (30%)						$3,100	$247		
PV solar tax incentive (30%)						$5,343	$427		
TVA generation partner ($1000)						$1,000	$80		
TVA in-home evaluation						$500	$40		
Federal energy retrofit tax incentive						$1,500	$120		
Total incremental cost to buyer including incentives						$30,684	$2,450	$410	Neutral Cost Criteria Not Met

CFL = compact fluorescent lightbulb; ERV = energy recovery ventilator; PV = photovoltaic; TVA = Tennessee Valley Authority

Without the solar PV, but including the solar water heater, neutral cash flow is not met after this first year's configuration of technologies. The house operation with all the energy-efficiency added features and with no available incentives would cost an additional $787/year more than the annualized mortgage and energy cost of the builder house. Subtracting federal and utility incentives available in April 2010 reduces this cost to $220; adding the solar PV site generation and the available tax and utility incentives for PV results in an annual cost for this house of $410/year. To bring this house to a neutral cost would require another incentive package for energy efficiency of $5140. This is within the levels of the energy-efficiency incentives being discussed in the national HOMESTAR jobs federal legislation for "Gold Star" in March 2010. This also provides some very insightful cost targets to use in finding and developing new technologies needed to attain affordable net zero energy.

The lighting, plug, and dryer loads assumed for CC3 total 4504 kWh. With aggressive energy management (home automation and mindful energy usage behavior), it is possible to reduce this load 30%. That would provide another annual energy savings of $125. If TVA would increase the solar buyback rate from $0.12/kWh to $0.155/kWh for houses that have a third-party certified HERS of less than 50 without the PV, this would provide the homeowner another $199/yr. If the incremental cost of constructing the R-22 $h{\cdot}ft^2{\cdot}°F/Btu$ ($3.9\ m^2{\cdot}°C/W$) walls from R-11 $h{\cdot}ft^2{\cdot}°F/Btu$ ($1.9\ m^2{\cdot}°C/W$) could be reduced 50%, that would provide $180. With the added homeowner energy efficiency, reduced incremental cost of constructing R-22 $h{\cdot}ft^2{\cdot}°F/Btu$ ($3.9\ m^2{\cdot}°C/W$) walls, and slightly increased solar buyback, this house would meet the BA neutral cost criteria. An increase in the residential electric rate from $0.093/kWh to $0.13/kWh would also allow this house to meet the neutral cash flow criteria.

Table 8 shows a list of the energy-efficiency and site generation technologies in CC3, prioritized from the best annualized cost to the worst. Included in the table are incentives for specific technologies but not those based on whole-house performance. Placing the ducts inside the conditioned space has the largest return on investment, followed by the change from two SEER 13 Btu/Wh (13.7 kJ/Wh) heat pumps totaling 4 tons (51 MJ) of capacity located outside the conditioned space in the builder house to a single 2 ton (25 MJ) zone-controlled SEER 16 Btu/Wh (16.9 kJ/Wh) unit positioned inside the conditioned space in CC3.

The ENERGY STAR fridge should clearly have a positive annual cost, but the fridge in the builder house was not rated as ENERGY STAR yet was clearly a very good refrigerator since the measured daily energy demand was 1.37 kWh/day compared to the ENERGY STAR fridge in CC3, which was measured over the same eight-month per period with identical automated door openings of 1.15 kWh/day. The BA benchmark fridge uses 1.83 kWh/day.

The radiant barrier located on the underside of the roof sheathing only cost an additional $207 for this house but, according to the EnergyGauge (FSEC 2009) model, predicts

Table 8. Prioritized List of Energy Efficiency and Site Generation Technologies by Annualized Cost

Technology	First Cost	Annual Cost
Ducts inside conditioned space	$2,000	-$184
SEER 16 heat pump	$1,000	-$128
CFL	$883	-$60
R-49 attic insulation	$300	-$32
ENERGY STAR washer and dryer	$700	-$31
Slab edge insulation of R-10	$400	-$3
move two windows from west and east to south	$2	-$2
ENERGY STAR fridge	$132	$4
U = 0.2 doors	$253	$6
Radiant barrier under roof sheathing	$207	$12
Windows double-pane to triple, low-e, gas filled	$1,900	$17
Improved ach from 5.8 to 2.4 @ 50 Pa	$800	$35
Improved floors over garage	$500	$39
ERV	$3,000	$219
Solar PV	$17,809	$269*
Improved walls from 13 to 22	$4,508	$277
Solar water heater	$9,733	$371*

*After rebates.
CFL = compact fluorescent lightbulb; ERV = energy recovery ventilator; PV = photovoltaic

an annual energy savings of $4.84 over the benchmark house. This converts to a simple payback of 43 years. This ventilated attic has R-49 h·ft^2·°F/Btu (8.9 m^2·°C/W) insulation over the ceiling joists and has no HVAC equipment.

The R-6 h·ft^2·°F/Btu (1.1 m^2·°C/W) windows for CC3 came very close to a positive cash flow. The triple-pane window incremental cost over the double-pane "no low-E no gas fill" was $8.30/ft^2 ($0.89/m^2). This was based on an invoice for the same type of triple-pane windows purchased for the author's office in September 2009.

The cost and energy savings resulting in the airtightness improvement in CC3 compared to the builder house is difficult to break out from the other individual technologies utilized in this building. The cost is based mostly on the lead carpenter's report that he spent an additional 40 hours providing backing and extra sealing in the walls and ceilings of CC3. Obviously there are many other features, such as having the ducts inside the conditioned space, better windows, foam flashing, and taped insulated sheathing board in the walls, that contribute to the airtightness. Most of the added cost in the floors above the garage and the cantilevered floor above the porch helped more with the airtightness than simply the added R-value, but only the energy savings of the modest increase in R-value was used in the model to allocate the energy savings for these improvements.

The ERV is another tough one to isolate. To mechanically ventilate, the power of the fans work against the energy savings. The cost to install these units with completely separate ducts sucking from the wet rooms and blowing to the dry comes with a significant first-cost expense. But added indoor air quality benefits that are not accounted for in the neutral cash flow analysis obviously come into play.

The solar PV system with the federal tax incentive of 30% and the TVA generation partnership and the buyback rate reduces the annual cost to $269. Reducing the installed cost of the PV system from $7.12/W to $5.20/W, or increasing the buyback rate from $0.12/kWh to $0.20/kWh, would be all it would take to make the 2.5 kW peak solar PV system in CC3 be cost neutral.

The relatively poor neutral cost performance of the walls is an artifact that these houses are *research* houses. They are rented out for research purposes from 2009 until the end of 2012. Every year in June the technology packages will change and the houses will be monitored for another year. The experimental plan called for extremely tight walls in CC3 because of the difficulty of retrofitting airtightness after initial construction. These walls have redundant air retarders, taped sheathing, and 1 in. of closed cell flashed foam sprayed against the inside of the sheathing. This effort contributes to the high annualized cost for the hot box measured R-22 h·ft^2·°F/Btu (3.9 m^2·°C/W) walls in CC3 compared to the nominal R-13 h·ft^2·°F/Btu (2.3 m^2·°C/W) (closer to whole-wall R-11 h·ft^2·°F/Btu (1.9 m^2·°C/W)) in the builder house.

The solar water heater had the worst payoff of all the technologies selected for this house. After the 30% federal tax incentive, compared to the all-electric 50 gal (189 L) water heater with an energy factor of 0.91in the builder house, this has an annual net cost of $371/year. For the solar water heater with 30% incentive to attain neutral cost in this house, the first cost needs to be less than $3700.

SUMMARY

This paper describes the measured energy and cost performance of a home that uses 68% less energy than the Builder Standard model. This three-bedroom, 2.5 bath, 2512 ft^2 (233 m^2) house has a Home Energy Rating System (HERS) index of 34 (a HERS rating of 0 is a zero-energy house; a conventional new house would have a HERS rating of 101). Without the PV system, CC3 maintains a 55% energy savings over the builder house.

The solar fraction for this West Knoxville, TN, house was found to be 29%. It is predicted that CC3 will require 11518 kWh, 4.5/kWh·ft^2 (0.4/kWh·m^2) of conditioned floor space. This data is based upon a calibrated EnergyGauge (FSEC 2009) simulation with a year's worth of measured data. The total energy cost to operate this house with three occupants is around a dollar a day.

The house is constructed with advanced 2 × 6 optimum value framing with structural insulated sheathing, spray foam, blown-in fiberglass, radiant barrier roof sheathing, an airtight envelope (2.40 air changes per hour at 50 Pa), triple-pane windows, an energy recovery ventilator, ducts inside the conditioned space, a home run (manifold and straight pipes to each end use) cross-linked polyethylene plumbing system, an extensive moisture control package, ENERGY STAR appliances, a solar water heater, and a 2.5 kWp photovoltaic system. The detailed specifications for the envelope and the equipment used in the two-story CC3 in comparison to the builder house are listed in Tables 1 and 2. The analysis compares the CC3 energy usage and the incremental cost of energy efficiency and solar technologies to the costs of the builder house.

Based on six months of 120 sensors detailing hourly measured data, a computer simulation of CC3 was generated and calibrated. This model is of the typical American occupancy patterns and energy services of three occupants. The energy consumption for this all-electric house is predicted to cost around \$1/day. In contrast, the builder house would require \$6.53/day (these costs are based on actual 2009 residential rates of \$0.093/kWh and solar buyback at \$0.213/kWh). Based on the six months of data, this all-electric home is predicted to use 30 kWh/day. The roof-mounted 2.5 kWp PV system is predicted to generate an average of 9 kWh/day.

The actual invoice level costs of constructing CC3 in 2008 were gathered with the builder's 15% profit and overhead to determine the total cost of construction of \$353,570, or \$141/ft^2 (\$13/m^2). After incentives and removal of added expenses due to the research nature of this project, the incremental construction cost is \$30,685. A detailed neutral cash flow analysis was conducted. With a higher residential electric rates, higher Tennessee Valley Authority solar buyback rates, and increased levels of homeowner energy efficiency and/or federal energy efficiency incentives, the performance attained in this house could be cash flow neutral. To achieve true zero energy a 30% reduction in lighting, plug, and dryer loads from that of the "typical" American household, an increase in PV capacity from 2.5 to 7.5 kW would be needed. This paper provides some cost targets for innovation needed to attain affordable zero energy homes in the future.

REFERENCES AND BIBLIOGRAPHY

ACCA. 2006. *Residential Duct Systems Manual D*. Arlington, VA: Air Conditioning Contractors of America.

ASHRAE. 2004. *ANSI/ASHRAE Standard 62.2-2004, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2007. *ANSI/ASHRAE Standard 62.2-2007, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 2002. *ASTM C518-10, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*. West Conshohocken, PA: ASTM International.

Christian, J.E. 1996. Thermal performance and wall ratings. *ASHRAE Journal* 38(3):56–65.

Christian, J.E. 2006. Energy savings from small near-zero-energy houses integration. FEMP Tech Alert, April. Federal Energy Management Program, Washington, DC.

Christian, J.E. 2008. 2600 ft^2 home that has 50% energy savings in the mixed-humid climate; ZEH5 2-Story. DOE 2007 to 2008 Study, May 2008. U.S. Department of Energy, Washington, DC.

Dockery, R., and J. Christian. 2010. 2512 ft^2 Home that has 75% DOE BA Energy Savings in the Mixed-Humid Climate: CC3 2-Story at Campbell Creek. ORNL Technical Report 2010/174, November. Oak Ridge National Laboratory, Oak Ridge, TN.

DOE. 2004. Typical appliance usage. In: *2004 Buildings Energy Databook*, Table 7.2. Washington, DC: U.S. Department of Energy.

EIA. 2010. Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State, Table 5.6.A. www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html. Washington, DC: U.S. Energy Information Administration.

FSEC. 2009. EnergyGauge Energy and Economic Analysis Software. Cocoa, FL: Florida Solar Energy Center.

Hendron, R., and C. Engebrent. 2009. Building America Research Benchmark Definition, Updated December 2009. NREL/TP-550-47246, www.eere.energy.gov/buildings/building_america/pdfs/40968.pdf. Golden, CO: National Renewable Energy Laboratory.

Hendron, R. 2006. Building America Performance Analysis Procedures, Rev. 1. NREL/TP-550-35567. Golden, CO: National Renewable Energy Laboratory.

ICC. 2006. *International Energy Conservation Code*. Washington, DC: International Code Council.

RESNET. 2002. RESNET Web site, http://resnet.us. Oceanside, CA: Residential Energy Services Network.

RReDC. 2008. National Solar Radiation Data Base, 1991–2005 Update: Typical Meteorological Year. 3http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/. Washington, DC: Renewable Resource Data Center, National Renewable Energy Laboratory.

Rutkowski, H. 2004. *Manual J Residential Load Calculation*, 8th ed. Arlington, VA: Air Conditioning Contractors of America.

SRCC. 2010. Solar Rating and Certification Corporation Web page, www.solar-rating.org. Cocoa, FL: Solar Rating and Certification Corporation.

TVA. 2010. Green Power Switch® Generation Partners℠ program, www.tva.gov/greenpowerswitch/partners/index.htm. Knoxville, TN: Tennessee Valley Authority.